Absorption in the fractional quantum Hall regime: trion dichroism and spin polarization

J. G. Groshaus [1,2,3,]* P. Plochocka-Polack [1], M. Rappaport [1], V. Umansky [1], and I. Bar-Joseph [1]

[1] *Department of Condensed Matter Physics, The Weizmann Institute of Science, Rehovot, Israel.*

B. S. Dennis [2], L. N Pfeiffer [2], K. W. West [2], Y. Gallais [3], and A. Pinczuk [2,3]

[2] *Bell Laboratories, Lucent Tech. Murray Hill, NJ 07974. and*

[3] *Department of of Physics and of Appl. Physics and Appl. Mathematics, Columbia University, New York, NY 10027*

(Dated: February 6, 2008)

We present measurements of optical interband absorption in the fractional quantum Hall regime in a GaAs quantum well in the range $0 < \nu \leq 1$. We investigate the mechanism of singlet trion absorption, and show that its circular dichroism can be used as a probe of the spin polarization of the ground state of the two-dimensional electron system (2DES). We find that at $\nu \leq 1/3$ the 2DES is fully spin-polarized. Increasing the filling factor results in a gradual depolarization, with a sharp minimum in the dichroism near $\nu = 2/3$. We find that in the range $0.5 \leq \nu < 0.85$ the 2DES remains partially polarized for the broad range of magnetic fields from 2.75 to 11 Tesla. This is consistent with the presence of a mixture of polarized and depolarized regions.

The electron-electron Coulomb interaction plays an important role in determining the spin polarization ($\mathcal{P}$) of a two-dimensional electron system (2DES) in a perpendicular magnetic field B. The effect of the interactions on the spin is most readily seen in in the filling factor range $\nu \leq 1$, where the level degeneracy exceeds the number of electrons. The exchange part of the Coulomb interactions favors a ferromagnetic state. However, a many-body wavefunction in which all electrons have the same spin is restricted by the Pauli principle and may not constitute in general an optimal spatial distribution that minimizes the total Coulomb energy. Inclusion of components of the opposite spin in the wavefunction opens a larger phase space for the electrons and may result in a lower Coulomb repulsion. Thus, the ground state of the 2DES in this regime is determined by the competition between the gain in Coulomb energy and the cost in Zeeman energy.

Several methods have been used to determine the 2DES spin polarization in the fractional quantum Hall regime. The direct method is measuring the shift in the nuclear magnetic resonance (NMR) caused by the 2DES magnetization. Indeed, NMR measurements have yielded quantitative measurements of $\mathcal{P}$ throughout a broad range of filling factors [1, 2]. Transport experiments have also been used and were successful in identifying transitions in the spin polarization, although are less effective in providing a quantitative value of $\mathcal{P}$ [3, 4].

An alternative approach for measuring $\mathcal{P}$ is using optical spectroscopy: photoluminescence [5], reflectivity [6], and absorption spectroscopy [7]. In these techniques, the occupation of each spin levels are obtained from measurements of the circular dichroism of the interband transitions. In quantum wells (QW), however, establishing the relation between the optical oscillator strengths (OS) and $\mathcal{P}$ presents a major difficulty. As a result of the strong interaction between the photo-created valence hole and the electrons, the spectrum in QWs is dominated by resonance peaks, associated with the neutral exciton, and charged excitons (trions). A further complication is introduced by the fact that in a trion, the two electrons can form a singlet or triplet wavefunctions [8, 9]. Hence, it is essential to take into account the nature and symmetry of these excitonic states [10].

In this paper we show that the 2DES spin polarization can be quantitatively determined by measuring the circular dichroism of the singlet trion absorption, $\mathcal{D}_T$, defined as $(I_{T_\downarrow} - I_{T_\uparrow})/(I_{T_\downarrow} + I_{T_\uparrow})$, where $I_{T_{\uparrow,\downarrow}}$ are the OS of the singlet trion peaks at the σ^+ (σ^-) circular light polarization. We apply this approach to back-gated quantum well samples, in which the 2DES density can be continuously varied. By determining the electron density dependence of $\mathcal{D}_T$ at different magnetic fields we map the spin polarization of a 2DES in the range $\nu < 1$. We find that the 2DES is spin polarized at $\nu \leq 1/3$, exhibits a gradual depolarization at $\nu > 1/3$, leveling at $\mathcal{P} \approx 1/2$, exhibit a sharp minimum near $\nu = 2/3$ and re-polarizes towards $\nu = 1$. We find that the results are largely independent on the magnetic field in the range studied. This is consistent with the proposed presence of magnetic domains [4, 11, 12, 13].

The experiments were done in a dilution fridge with optical windows at a base temperature of 70 mK, and a magnetic field applied along the growth axis of the wafer. Two experimental techniques were implemented to measure the absorption spectrum. The first is based on measuring the photocurrent (PC) flowing between the 2DES and a back-gate. The sample is illuminated by a tunable dye laser with power densities of $\sim 5 \times 10^{-4}$ W/cm^2 through a circular polarizer, and the PC is measured as a function of the photon energy [10]. In the second technique we incorporate a Bragg mirror between the 2DES and the back gate. White light at normal incidence (< 1 nW) is back reflected from this mirror, and passes twice
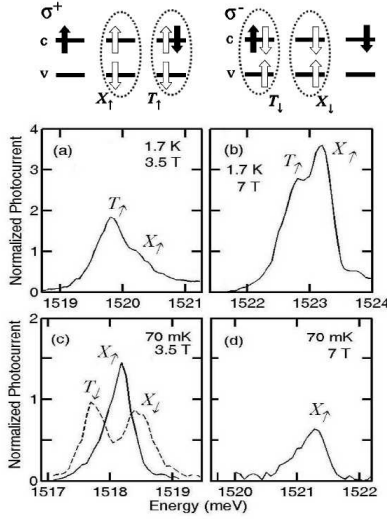
FIG. 1: (upper scheme) The mechanisms for absorption in quantum wells for both light polarizations. Horizontal lines represent orbitals in the conduction and valence band, c and v. Black arrows are preexisting electrons in the 2DES, and white arrows are photo-created electron-hole pairs. A photo-excited pair overlapping an existing electron, binds it forming a singlet trion; (a,b,c,d) Photocurrent (PC) spectra at $\nu = 1/3$ for absorption into the lower and upper Zeeman level (solid and dashed lines lines, respectively. For clarity, the spectra at each gate voltage is normalized by the PC efficiency, namely, we divide by the the PC signal at $B = 0$ at photon energies well above the Fermi energy, where the absorption is assumed to be independent of the voltage.

through the QW. Thus, the reflected spectra, divided by the signal at energies below the gap, yields the transmission spectrum.

Two samples were measured: Sample 1 was used for the PC measurements and consists of a single 20 nm $GaAs/Al_{0.12}Ga_{0.82}As$ modulation-doped QW grown on top of a 1.7 μm $Al_{0.3}Ga_{0.7}As$ barrier layer, separating it from the back-gate layer. Sample 2 was used for the transmission measurements and includes in addition a Bragg reflector, consisting of 20 pairs of AlAs and $Al_{0.3}Ga_{0.60}As$ layers. The wafers were processed to a mesa structure with selective ohmic contacts to the 2DES and to the back-gate. Applying a voltage between the 2DES and the back-gate we could tune the electron density continuously in the range $1 \times 10^{10} - 1 \times 10^{11}$ cm^{-2} in sample 1 and $5 \times 10^{10} - 3 \times 10^{11}$ in sample 2.

The solid lines in Fig. 1 depict four photocurrent spectra at the σ^+ light polarization (absorption into the lower Zeeman level) for two magnetic fields, 3.5 and 7 T, and two temperatures, 1.7 K and 70 mK, at approximately constant $\nu \approx 1/3$. It is seen that the spectra at 1.7 K consist of two peaks: $T_\uparrow$ and $X_\uparrow$. However, as the sample is cooled to 70 mK - the $T_\uparrow$ peak completely disappears.

This striking behavior can be understood by noting the *singlet* nature of the $T_{\uparrow,\downarrow}$ trionic states. The symmetrical

nature of the spatial wavefunction of the electrons in the trion implies that it is formed when an electron is photo-created in an orbital where an electron with *opposite* spin is already present. For example, the $T_\uparrow$ transition occurs when a σ^+ photon creates an $\uparrow$-electron (in the lower Zeeman level) in spatial orbitals which are occupied by $\downarrow$-electrons (see the upper scheme of Fig. 1). Thus, the probability of creating the $T_\uparrow$ state will depend not only on the phase space available for absorption into $\uparrow$-states, but also on the total number of $\downarrow$-electrons. The X peaks, on the other hand, are formed when an electron is photo-created in unoccupied orbitals [15].

Within this picture, the spectrum is readily explained: at 1.7 K the 2DES is not spin-polarized, and hence $\downarrow$-electrons are present at the upper Zeeman level. These $\downarrow$- electrons can pair with the photo-created $\uparrow$-electron giving rise to the $T_\uparrow$ peak. As the sample is cooled to 70 mK at $\nu = 1/3$, the 2DES becomes spin-polarized, and the absence of $\downarrow$-electrons results in a the quenching of the $T_\uparrow$ peak. This interpretation is confirmed by the fact that in absorption to the upper Zeeman level (Fig. 1c, dashed line), the $T_\downarrow$ peak persists at low temperatures: there are always $\uparrow$-electrons to pair with the photo-created $\downarrow$-electron. The resulting dichroism, $\mathcal{D}_T$, is equal to 1.

Increasing the density above $\nu = 1/3$ we find that the $T_\uparrow$ peak, which was absent at $\nu \leq 1/3$, gradually appears and gains strength, indicating a loss of spin polarization. This is demonstrated in Fig. 2a, which shows the σ^+ spectra at $T = 70$ mK and constant magnetic field, $B = 4$ T, for $0.3 \lesssim \nu \lesssim 0.7$. It is seen that around $\nu \approx 2/3$ the $T_\uparrow$ peak is already well developed. Figure 2b shows spectra taken at $\nu \approx 2/3$ at several magnetic fields, $2.75 < B < 5$ T. It is seen that the $T_\uparrow$ peak exists in all spectra, and becomes the dominant one as the field increases. These indications for depolarization above $\nu = 1/3$ are observed over a relatively broad magnetic field range. Unfortunately, however, at high fields ($B \geq 7$ T) the spectral lines in this sample are broadened near $\nu = 1/3$ and the trion peak height cannot be reliably resolved.

To obtain the single trion circular dichroism we determine $I_{T_\uparrow}$ and $I_{T_\downarrow}$ by taking the area under each of the corresponding T peaks. Figure 3 shows $\mathcal{D}_T$ as a function of ν at two magnetic fields, $B = 2.75$ and 5 T. Remarkably, we find a similar dependence of $\mathcal{D}_T$ on ν throughout this magnetic field range: $\mathcal{D}_T \approx 1$ at $\nu \leq 1/3$, exhibits a fast decrease at $\nu > 1/3$, leveling at $\mathcal{D}_T \approx 1/2$, and increases again to $\mathcal{D}_T \approx 1$ at $\nu = 1$.

To interpret these results, we need to relate the trion absorption, $I_{T_{\uparrow,\downarrow}}$, to the spin polarization. Since the photo-created electron needs to pair with an opposite spin, we model the OS of each T peak as proportional to the number of unpaired electrons with opposite spin, i.e.
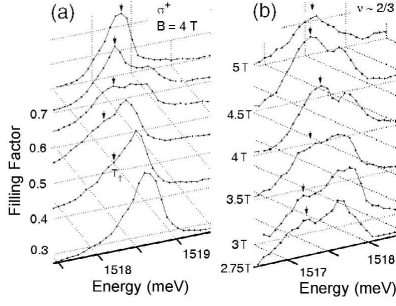
FIG. 2: Normalized photocurrent spectra at the σ^+ light polarization: (a) at constant field ($B = 4$ T) for several ν. As ν increases above 1/3, the $T_\uparrow$-peak, marked by the arrows, appears and increases. (b) At constant ν ($\sim 2/3$) for several B. The $T_\uparrow$-peak is present throughout the range, and increases with the electron density.
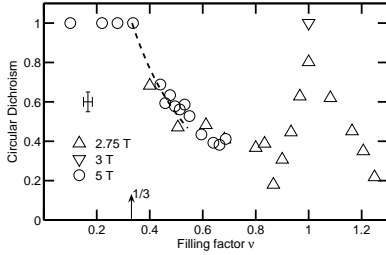

FIG. 3: The circular dichroism of the singlet trion absorbtion, $\mathcal{D}_T$. The dashed line is the theoretical depolarization caused by a quasiparticle of $\mathcal{S} = 0.23$. The error bar shows typical errors in ν and $\mathcal{D}_T$. The values shown for $\nu > 1$ are given by $(2-\nu)/\nu \, \mathcal{D}_T$) [16].

$$I_{T_\uparrow} = Cf_\downarrow N_\downarrow = Cf_\downarrow N_e \frac{1}{2}(1 - \mathcal{P}) \qquad (1)$$
$$I_{T_\downarrow} = Cf_\uparrow N_\uparrow = Cf_\uparrow N_e \frac{1}{2}(1 + \mathcal{P}).$$

Here $N_{\downarrow(\uparrow)}$ are the number of $\downarrow$ ($\uparrow$)-electrons, $\mathcal{P} \equiv (N_\downarrow - N_\uparrow)/N_e$, and C is a proportionality constant, which may depend on B and ν, and includes the PC efficiency. The factor $f_{\downarrow(\uparrow)}$ is the fraction of $\downarrow$ ($\uparrow$) - electrons that are *unpaired*, i.e. that occupy orbitals where the state of opposite spin is empty. In an uncorrelated gas in the lowest Landau level approximation, this factors are proportional to the single-particle phase space available, i.e. $f_\downarrow = 1 - N_\uparrow/N_\phi$. In a strongly correlated 2DES, the Coulomb repulsion tends to minimize the number of paired electrons. Therefore, for $\nu \leq 1$, we shall assume that in the ground state all the electrons are unpaired, i.e. $f_{\downarrow,(\uparrow)} = 1$. It can be seen from Eq. 1 that both $I_{T_{\uparrow,\downarrow}}$ are expected to increase with N_e. Figure 2b demonstrates this for the $T_\uparrow$ peak: the increase of the peak with magnetic field at constant ν is due to the increased electron density. The $T_\downarrow$ peak increases accordingly (not shown).

The relation between the spin polarization, $\mathcal{P}$, and the

dichroism $\mathcal{D}_T$ turns out to be surprisingly simple. Using Eq. 1, $\mathcal{P}$ can be expressed (for $\nu \leq 1$ [16]) as

$$\mathcal{P} = \frac{I_{T_\uparrow} - I_{T_\downarrow}}{I_{T_\uparrow} + I_{T_\downarrow}}, \qquad (2)$$

namely, $\mathcal{P} = \mathcal{D}_T$. This model allows us to interpret the measurements. We focus first on the behavior around $\nu = 1/3$ in fig. 3. As expected [17] we find that the 2DES is spin polarized at $\nu = 1/3$. Near this filling factor the polarization curve is highly asymmetric: the 2DES is spin polarized at $\nu \lesssim 1/3$, and gradually depolarizes at $\nu > 1/3$.

The depolarization can be expressed in terms of the number of spin flips, $\mathcal{S}$, caused by changing the magnetic flux by one quanta: $\mathcal{P}(\nu > \nu_0) = 1 - 2|1/\nu_0 - 1/\nu|\mathcal{S}$, where $\nu_0 = 1/3$. A similar expression can be written for $\nu < \nu_0$, where the change in spin per flux is denoted as $\mathcal{A}$. The dashed line in Fig. 3 is a fit to the above expression with $\mathcal{S} = 0.23$. Within our experimental error we cannot rule out some depolarization at $\nu < 1/3$, yet an asymmetric behavior is evident, with $\mathcal{A} << \mathcal{S}$. An similar asymmetry in $\mathcal{P}$ around $\nu = 1/3$ was also observed by NMR with $\mathcal{S} \sim 0.1$ around 12 T [1]. The fact that $\mathcal{S} < 1$ is surprising: charge excitation of a quasiparticle with a reversed spin $1/2$ is expected to yield a net change of spin equal to 1, and a more complex quasiparticle, such as a Composite Fermion Skyrmion [18] should cause several spin-flips per one flux quanta, i.e - $\mathcal{S} \geq 1$. This behavior could be due to a spatial inhomogeneity in the spin polarization [12]. Accordingly, the 2DES consists of regions with $\mathcal{P} = 0$ and $\mathcal{P} = 1$, and the rate of change in $\mathcal{P}$ represents the gradual change in this mixture.

Let us turn now to the region around $\nu = 2/3$. Figures 4a and 4b show the measured absorption spectra around this filling factor at 11 T, at 70 mK in sample 2, in the lower (σ^-) and upper Zeeman level (σ^-). It is clearly seen that the area of the $T_\downarrow$ peak (σ^-) is minimal at $\nu = 2/3$ (blue line). Simultaneously, the area of the $T_\uparrow$ peak (σ^+) is maximal at the same filling factor (even though the peak height at $\nu = 0.7$ and 0.75 are higher), resulting in a dip in the dichroism. In Fig. 4c we show the dichroism for a broad range of magnetic fields, $5-11$ T. It is seen that a minimum of the dichroism always appears in the vicinity of $\nu = 2/3$. Within the uncertainty in filling factor, we are not able to determine in our work if $\nu = 2/3$ falls inside the dip. It is possible that $\mathcal{P}$ remains constant for $1/2 \geq \nu \leq 2/3$, and then above 2/3 there is a rapid depolarization, as was found in Ref. [2]. The dashed line in Fig. 4c shows the depolarization rate with $\mathcal{S} = 1$, and it is seen that it fits well to our data. Such depolarization rate was also found in Ref. [2] above 2/3.

We observe that over the range of intermediate filling factors, $0.5 \leq \nu \leq 0.85$, the 2DES remains about half polarized for the whole range of magnetic fields. In a model of non-interacting composite Fermions (CF) [21] $\mathcal{P}$ is ex-
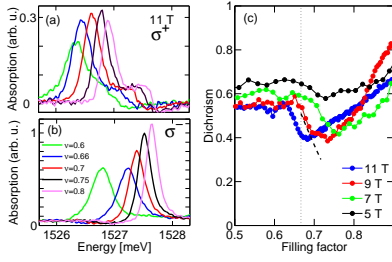
FIG. 4: (a), (b) The absorption spectrum at at 70 mK and $B = 11$ T for σ^- and σ^+ polarizaion (absorption to the upper and lowe Zeeman, respectively) for several filling factors around $\nu = 2/3$. (c) The circular dichroism of the trion absorption at several magnetic fields. The dashed line is $\mathcal{P} = \frac{1}{2} - 2|1/\nu_0 - 1/\nu|\mathcal{S}$, where $\nu_0 = 2/3$, and $\mathcal{S} = 1$.

pected to be determined by the ratio between Zeeman, E_z, and Coulomb energies, E_C, often represented by the parameter $\eta = E_Z/E_C = 0.0057\sqrt{B}$ (for perpendicular fields). Here $E_Z = |g|\mu_B B$, and $E_C = \frac{e^2}{\epsilon}\sqrt{eB/(\hbar c)}$. In this model, at $\nu = 2/3$ as η is increased across a critical value η_c, at which the Zeeman energy equals the CF-cyclotron gap, the polarization is expected to undergo a sharp transition from 0 to 1. At $\nu = 1/2$, the polarization is expected to raise as $\mathcal{P} = \eta/\eta_c$, until the Zeeman energy equals the CF-Fermi energy, and $\mathcal{P}$ for $\eta > \eta_c$. For $\nu = 2/3$, the value of η_c in literature varies in the range $0.008 - 0.0185$ [2, 3, 4, 5, 14]. For $\nu = 1/2$, it was found that $\eta_c = 0.022$ [2], and $0.0166 - 0.018$ [5, 19]. In our samples we find that the η_c for all filling factors between $1/2$ and 1 should be higher than our range ($\eta_c > 0.0189$).

The fact that at $\nu = 2/3$ the spin polarization does not vanish for a large range of η below η_c is remarkable, and it has been observed before for smaller range of η [2]. The effect of residual CF-CF interactions, disorder, spin-orbit coupling predict a partially polarized phase for a much smaller range of η [20]. Recently, a model based on the effect of the lattice potential predicted the existence of inhomogeneous magnetic domains, resulting in a state with average $\mathcal{P} = 1/2$ for broader range of η [11]. Experimental evidence for the existence of domains was provided by recent spectroscopic NMR measurements [12], by the observation of the breaking in the selection rules for phonon excitation [13], and by the hysteresis of η_c in transport [4]. Both the rate of depolarization around $1/3$ and the partial polarization state found around $2/3$ and $1/2$ are consistent with this explanation.

* Electronic address: jgg@phys.columbia.edu
[1] P. Khandelwal *et al.*, Phys. Rev. Lett. **81**, 673 (1998)
[2] N. Freytag *et al.*, Phys. Rev. Lett. **87**, 136801 (2001); N. Freytag *et al.*, Phys. Rev. Lett. **89**, 246804 (2002).
[3] J. P. Eisenstein, in *Perspectives in Quantum Hall Effects*, edited by S. Das Sarma and A. Piczuk (Wiley, New York, 1999). J. Eisenstein *et al.*, Phys. Rev. Lett. **62**, 1540 (1989); L. W. Engel *et al.*, Phys. Rev. B **45**, 3418 (1992).
[4] J. H. Smet *et al.*, Phys. Rev. Lett. **86**, 2412 (2001); J.H. Smet, *et al.*, Nature **415**, 281 (2002).
[5] I.V. Kukushkin *et al.,* Phys. Rev. Lett. **82**, 3665 (1999); I.V. Kukushkin *et al.,* Phys. Rev. Lett. **85**, 3688 (2000).
[6] R. Chughtai *et al.*, Phys. Rev. B **65**, 161305(R) (2002).
[7] E.H. Aifer *et al.*, Phys. Rev. Lett. **76**, 680 (1996); M.J. Manfra *et al.*, Phys. Rev. B 54 R17327 (1996).
[8] G. Yusa, H. Shtrikman, and I. Bar-Joseph, Phys. Rev. Lett. **87**, 216402 (2001); K. Kheng *et al.*, Phys. Rev. Lett. 71 1752 (1993); D. R. Yakovlev *et al.,* Phys. Rev. Lett. 79, 3974, (1997).
[9] A. Wojs and P. Hawrylak, Phys. Rev. B 51, 10 880 (1995); A. Wojs, J. J. Quinn and P. Hawrylak Phys. Rev. B **62**, 4630 (2000).
[10] J.G. Groshaus *et al.* Phys. Rev. Lett. **93**, 96802 (2004).
[11] G. Murthy, Phys. Rev. Lett. **84**, 350 (2000).
[12] O. Stern, *et al.*, Phys. Rev. B **70**, 75318 (2004).
[13] F. Schulze-Wischeler *et al.*, Phys. Rev. Lett. **93**, 26801 (2004); F. Schulze-Wischeler *et al.*, Int. J. Mod. Phys. B **18**, 3857 (2004).
[14] F. Schulze-Wischeler, E. Mariani, F. Hohls, and R. J. Haug Phys. Rev. Lett. **92**, 156401 (2004).
[15] The X peak could be associated with the triplet trion, where the second electron is weakly bound.
[16] For $\nu \geq 1$, not all electrons are unpaired. We assume that the number of doubly occupied orbitals is $N_e - N_\phi$, and thus, $f_{\downarrow,\uparrow} = [N_{\downarrow,\uparrow} - (N_e - N_\phi)]/N_{\downarrow,\uparrow}$. Consequently, the expression for $\mathcal{P}$ for $\nu \geq 1$ from Eq. 2 needs to be multiplied by $(2 - \nu)/\nu$.
[17] R. B. Laughlin, Phys. Rev. Lett. **50**, 1395 (1983); Rev. Mod. Phys. **71**, 863 (1999).
[18] R. K. Kamilla *et al.*, Sol. Stat. Com. **99**, 289 (1996); D. R. Leadley *et al.*, Phys. Rev. Lett. **79**, 4246 (1997); A. F. Dethlefsen *et al.*, arXiv:cond-mat/0508393 (2005); A. F. Dethlefsen *et al.*, arXiv:cond-mat/0603455 (2005).
[19] Ref [5] shows that the critical field is sensitive to the effective width of a 2DES. See also: S. S. Mandal and J. K. Jain, Phys. Rev. B **64**, 125310 (2001).
[20] E. Mariani *et al.*, Phys. Rev. B **66**, 241303(R) (2002); K. Vyborny and D. Pfannkuche, Int. J. Mod. Phys B **18** 3871 (2004).
[21] J.K. Jain, Phys. Rev. Lett. **63**, 199 (1989); B.I. Halperin *et al.*, Phys. Rev. B **47**, 7312 (1993); K. Park and J.K. Jain, Phys. Rev. Lett. **80**, 4237 (1998).